# 6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

**Table 6.1.** Revised May 2002 by D.E. Groom (LBNL). Gases are evaluated at 20°C and 1 atm (in parentheses) or at STP [square brackets]. Densities and refractive indices without parentheses or brackets are for solids or liquids, or are for cryogenic liquids at the indicated boiling point (BP) at 1 atm. Refractive indices are evaluated at the sodium D line. Data for compounds and mixtures are from Refs. 1 and 2. Futher materials and properties are given in Ref. 3 and at `http://pdg.lbl.gov/AtomicNuclearProperties`.

| Material | $Z$ | $A$ | $\langle Z/A\rangle$ | Nuclear [a] collision length $\lambda_T$ {g/cm$^2$} | Nuclear [a] interaction length $\lambda_I$ {g/cm$^2$} | $dE/dx\|_{\rm min}$ [b] $\left\{\frac{\rm MeV}{\rm g/cm^2}\right\}$ | Radiation length [c] $X_0$ {g/cm$^2$} | {cm} | Density {g/cm$^3$} ({g/$\ell$} for gas) | Liquid boiling point at 1 atm(K) | Refractive index $n$ ($(n-1)\times10^6$ for gas) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $H_2$ gas | 1 | 1.00794 | 0.99212 | 43.3 | 50.8 | (4.103) | 61.28 [d] | (731000) | (0.0838)[0.0899] | | [139.2] |
| $H_2$ liquid | 1 | 1.00794 | 0.99212 | 43.3 | 50.8 | 4.034 | 61.28 [d] | 866 | 0.0708 | 20.39 | 1.112 |
| $D_2$ | 1 | 2.0140 | 0.49652 | 45.7 | 54.7 | (2.052) | 122.4 | 724 | 0.169[0.179] | 23.65 | 1.128 [138] |
| He | 2 | 4.002602 | 0.49968 | 49.9 | 65.1 | (1.937) | 94.32 | 756 | 0.1249[0.1786] | 4.224 | 1.024 [34.9] |
| Li | 3 | 6.941 | 0.43221 | 54.6 | 73.4 | 1.639 | 82.76 | 155 | 0.534 | | — |
| Be | 4 | 9.012182 | 0.44384 | 55.8 | 75.2 | 1.594 | 65.19 | 35.28 | 1.848 | | — |
| C | 6 | 12.011 | 0.49954 | 60.2 | 86.3 | 1.745 | 42.70 | 18.8 | 2.265 [e] | | — |
| $N_2$ | 7 | 14.00674 | 0.49976 | 61.4 | 87.8 | (1.825) | 37.99 | 47.1 | 0.8073[1.250] | 77.36 | 1.205 [298] |
| $O_2$ | 8 | 15.9994 | 0.50002 | 63.2 | 91.0 | (1.801) | 34.24 | 30.0 | 1.141[1.428] | 90.18 | 1.22 [296] |
| $F_2$ | 9 | 18.9984032 | 0.47372 | 65.5 | 95.3 | (1.675) | 32.93 | 21.85 | 1.507[1.696] | 85.24 | [195] |
| Ne | 10 | 20.1797 | 0.49555 | 66.1 | 96.6 | (1.724) | 28.94 | 24.0 | 1.204[0.9005] | 27.09 | 1.092 [67.1] |
| Al | 13 | 26.981539 | 0.48181 | 70.6 | 106.4 | 1.615 | 24.01 | 8.9 | 2.70 | | — |
| Si | 14 | 28.0855 | 0.49848 | 70.6 | 106.0 | 1.664 | 21.82 | 9.36 | 2.33 | | 3.95 |
| Ar | 18 | 39.948 | 0.45059 | 76.4 | 117.2 | (1.519) | 19.55 | 14.0 | 1.396[1.782] | 87.28 | 1.233 [283] |
| Ti | 22 | 47.867 | 0.45948 | 79.9 | 124.9 | 1.476 | 16.17 | 3.56 | 4.54 | | — |
| Fe | 26 | 55.845 | 0.46556 | 82.8 | 131.9 | 1.451 | 13.84 | 1.76 | 7.87 | | — |
| Cu | 29 | 63.546 | 0.45636 | 85.6 | 134.9 | 1.403 | 12.86 | 1.43 | 8.96 | | — |
| Ge | 32 | 72.61 | 0.44071 | 88.3 | 140.5 | 1.371 | 12.25 | 2.30 | 5.323 | | — |
| Sn | 50 | 118.710 | 0.42120 | 100.2 | 163 | 1.264 | 8.82 | 1.21 | 7.31 | | — |
| Xe | 54 | 131.29 | 0.41130 | 102.8 | 169 | (1.255) | 8.48 | 2.87 | 2.953[5.858] | 165.1 | [701] |
| W | 74 | 183.84 | 0.40250 | 110.3 | 185 | 1.145 | 6.76 | 0.35 | 19.3 | | — |
| Pt | 78 | 195.08 | 0.39984 | 113.3 | 189.7 | 1.129 | 6.54 | 0.305 | 21.45 | | — |
| Pb | 82 | 207.2 | 0.39575 | 116.2 | 194 | 1.123 | 6.37 | 0.56 | 11.35 | | — |
| U | 92 | 238.0289 | 0.38651 | 117.0 | 199 | 1.082 | 6.00 | ≈0.32 | ≈18.95 | | — |
| Air, (20°C, 1 atm.), [STP] | | | 0.49919 | 62.0 | 90.0 | (1.815) | 36.66 | [30420] | (1.205)[1.2931] | 78.8 | (273) [293] |
| $H_2O$ | | | 0.55509 | 60.1 | 83.6 | 1.991 | 36.08 | 36.1 | 1.00 | 373.15 | 1.33 |
| $CO_2$ gas | | | 0.49989 | 62.4 | 89.7 | (1.819) | 36.2 | [18310] | [1.977] | | [410] |
| $CO_2$ solid (dry ice) | | | 0.49989 | 62.4 | 89.7 | 1.787 | 36.2 | 23.2 | 1.563 | sublimes | — |
| Shielding concrete [f] | | | 0.50274 | 67.4 | 99.9 | 1.711 | 26.7 | 10.7 | 2.5 | | — |
| $SiO_2$ (fused quartz) | | | 0.49926 | 66.5 | 97.4 | 1.699 | 27.05 | 12.3 | 2.20 [g] | | 1.458 |
| Dimethyl ether, $(CH_3)_2O$ | | | 0.54778 | 59.4 | 82.9 | — | 38.89 | — | — | 248.7 | — |
| Methane, $CH_4$ | | | 0.62333 | 54.8 | 73.4 | (2.417) | 46.22 | [64850] | 0.4224[0.717] | 111.7 | [444] |
| Ethane, $C_2H_6$ | | | 0.59861 | 55.8 | 75.7 | (2.304) | 45.47 | [34035] | 0.509(1.356) [h] | 184.5 | (1.038) [h] |
| Propane, $C_3H_8$ | | | 0.58962 | 56.2 | 76.5 | (2.262) | 45.20 | — | (1.879) | 231.1 | — |
| Isobutane, $(CH_3)_2CHCH_3$ | | | 0.58496 | 56.4 | 77.0 | (2.239) | 45.07 | [16930] | [2.67] | 261.42 | [1900] |
| Octane, liquid, $CH_3(CH_2)_6CH_3$ | | | 0.57778 | 56.7 | 77.7 | 2.123 | 44.86 | 63.8 | 0.703 | 398.8 | 1.397 |
| Paraffin wax, $CH_3(CH_2)_{n\approx23}CH_3$ | | | 0.57275 | 56.9 | 78.2 | 2.087 | 44.71 | 48.1 | 0.93 | | — |
| Nylon, type 6 [i] | | | 0.54790 | 58.5 | 81.5 | 1.974 | 41.84 | 36.7 | 1.14 | | — |
| Polycarbonate (Lexan) [j] | | | 0.52697 | 59.5 | 83.9 | 1.886 | 41.46 | 34.6 | 1.20 | | — |
| Polyethylene terephthlate (Mylar) [k] | | | 0.52037 | 60.2 | 85.7 | 1.848 | 39.95 | 28.7 | 1.39 | | — |
| Polyethylene [l] | | | 0.57034 | 57.0 | 78.4 | 2.076 | 44.64 | ≈47.9 | 0.92–0.95 | | — |
| Polyimide film (Kapton) [m] | | | 0.51264 | 60.3 | 85.8 | 1.820 | 40.56 | 28.6 | 1.42 | | — |
| Lucite, Plexiglas [n] | | | 0.53937 | 59.3 | 83.0 | 1.929 | 40.49 | ≈34.4 | 1.16–1.20 | | ≈1.49 |
| Polystyrene, scintillator [o] | | | 0.53768 | 58.5 | 81.9 | 1.936 | 43.72 | 42.4 | 1.032 | | 1.581 |
| Polytetrafluoroethylene (Teflon) [p] | | | 0.47992 | 64.2 | 93.0 | 1.671 | 34.84 | 15.8 | 2.20 | | — |
| Polyvinyltolulene, scintillator [q] | | | 0.54155 | 58.3 | 81.5 | 1.956 | 43.83 | 42.5 | 1.032 | | — |
| Aluminum oxide ($Al_2O_3$) | | | 0.49038 | 67.0 | 98.9 | 1.647 | 27.94 | 7.04 | 3.97 | | 1.761 |
| Barium fluoride ($BaF_2$) | | | 0.42207 | 92.0 | 145 | 1.303 | 9.91 | 2.05 | 4.89 | | 1.56 |
| Bismuth germanate (BGO) [r] | | | 0.42065 | 98.2 | 157 | 1.251 | 7.97 | 1.12 | 7.1 | | 2.15 |
| Cesium iodide (CsI) | | | 0.41569 | 102 | 167 | 1.243 | 8.39 | 1.85 | 4.53 | | 1.80 |
| Lithium fluoride (LiF) | | | 0.46262 | 62.2 | 88.2 | 1.614 | 39.25 | 14.91 | 2.632 | | 1.392 |
| Sodium fluoride (NaF) | | | 0.47632 | 66.9 | 98.3 | 1.69 | 29.87 | 11.68 | 2.558 | | 1.336 |
| Sodium iodide (NaI) | | | 0.42697 | 94.6 | 151 | 1.305 | 9.49 | 2.59 | 3.67 | | 1.775 |
| Silica Aerogel [s] | | | 0.50093 | 66.3 | 96.9 | 1.740 | 27.25 | 136@$\rho$=0.2 | 0.04–0.6 | | 1.0+0.21$\rho$ |
| NEMA G10 plate [t] | | | | 62.6 | 90.2 | 1.87 | 33.0 | 19.4 | 1.7 | | — |

| Material | Dielectric constant ($\kappa = \epsilon/\epsilon_0$) () is ($\kappa$–1)×$10^6$ for gas | Young's modulus [$10^6$ psi] | Coeff. of thermal expansion [$10^{-6}$cm/cm-°C] | Specific heat [cal/g-°C] | Electrical resistivity [$\mu\Omega$cm(@°C)] | Thermal conductivity [cal/cm-°C-sec] |
|---|---|---|---|---|---|---|
| $H_2$ | (253.9) | — | — | — | — | — |
| He | (64) | — | — | — | — | — |
| Li | — | — | 56 | 0.86 | 8.55(0°) | 0.17 |
| Be | — | 37 | 12.4 | 0.436 | 5.885(0°) | 0.38 |
| C | — | 0.7 | 0.6–4.3 | 0.165 | 1375(0°) | 0.057 |
| $N_2$ | (548.5) | — | — | — | — | — |
| $O_2$ | (495) | — | — | — | — | — |
| Ne | (127) | — | — | — | — | — |
| Al | — | 10 | 23.9 | 0.215 | 2.65(20°) | 0.53 |
| Si | 11.9 | 16 | 2.8–7.3 | 0.162 | — | 0.20 |
| Ar | (517) | — | — | — | — | — |
| Ti | — | 16.8 | 8.5 | 0.126 | 50(0°) | — |
| Fe | — | 28.5 | 11.7 | 0.11 | 9.71(20°) | 0.18 |
| Cu | — | 16 | 16.5 | 0.092 | 1.67(20°) | 0.94 |
| Ge | 16.0 | — | 5.75 | 0.073 | — | 0.14 |
| Sn | — | 6 | 20 | 0.052 | 11.5(20°) | 0.16 |
| Xe | — | — | — | — | — | — |
| W | — | 50 | 4.4 | 0.032 | 5.5(20°) | 0.48 |
| Pt | — | 21 | 8.9 | 0.032 | 9.83(0°) | 0.17 |
| Pb | — | 2.6 | 29.3 | 0.038 | 20.65(20°) | 0.083 |
| U | — | — | 36.1 | 0.028 | 29(20°) | 0.064 |


1. R.M. Sternheimer, M.J. Berger, and S.M. Seltzer, Atomic Data and Nuclear Data Tables **30**, 261–271 (1984).
2. S.M. Seltzer and M.J. Berger, Int. J. Appl. Radiat. **33**, 1189–1218 (1982).
3. D.E. Groom, N.V. Mokhov, and S.I. Striganov, "Muon stopping-power and range tables," Atomic Data and Nuclear Data Tables **78**, 183–356 (2001).
4. S.M. Seltzer and M.J. Berger, Int. J. Appl. Radiat. **35**, 665 (1984) & `http://physics.nist.gov/PhysRefData/Star/Text/contents.html`.


*a.* $\sigma_T$, $\lambda_T$ and $\lambda_I$ are energy dependent. Values quoted apply to high energy range, where energy dependence is weak. Mean free path between collisions ($\lambda_T$) or inelastic interactions ($\lambda_I$), calculated from $\lambda^{-1} = N_A \sum w_j \sigma_j / A_j$, where $N$ is Avogadro's number and $w_j$ is the weight fraction of the $j$th element in the element, compound, or mixture. $\sigma_{\rm total}$ at 80–240 GeV for neutrons ($\approx \sigma$ for protons) from Murthy *et al.*, Nucl. Phys. **B92**, 269 (1975). This scales approximately as $A^{0.77}$. $\sigma_{\rm inelastic} = \sigma_{\rm total} - \sigma_{\rm elastic} - \sigma_{\rm quasielastic}$; for neutrons at 60–375 GeV from Roberts *et al.*, Nucl. Phys. **B159**, 56 (1979). For protons and other particles, see Carroll *et al.*, Phys. Lett. **80B**, 319 (1979); note that $\sigma_I(p) \approx \sigma_I(n)$. $\sigma_I$ scales approximately as $A^{0.71}$.

*b.* For minimum-ionizing muons (results are very slightly different for other particles). Minimum $dE/dx$ from Ref. 3, using density effect correction coefficients from Ref. 1. For electrons and positrons see Ref. 4. Ionization energy loss is discussed in Sec. 26.

*c.* From Y.S. Tsai, Rev. Mod. Phys. **46**, 815 (1974); $X_0$ data for all elements up to uranium are given. Corrections for molecular binding applied for $H_2$ and $D_2$. For atomic H, $X_0 = 63.05$ g/cm$^2$.

*d.* For molecular hydrogen (deuterium). For atomic H, $X_0 = 63.047$ g cm$^{-2}$.

*e.* For pure graphite; industrial graphite density may vary 2.1–2.3 g/cm$^3$.

*f.* Standard shielding blocks, typical composition $O_2$ 52%, Si 32.5%, Ca 6%, Na 1.5%, Fe 2%, Al 4%, plus reinforcing iron bars. The attenuation length, $\ell = 115 \pm 5$ g/cm$^2$, is also valid for earth (typical $\rho = 2.15$), from CERN–LRL–RHEL Shielding exp., UCRL–17841 (1968).

*g.* For typical fused quartz. The specific gravity of crystalline quartz is 2.64.

*h.* Solid ethane density at −60°C; gaseous refractive index at 0°C, 546 mm pressure.

*i.* Nylon, Type 6, $(NH(CH_2)_5CO)_n$

*j.* Polycarbonate (Lexan), $(C_{16}H_{14}O_3)_n$

*k.* Polyethylene terephthlate, monomer, $C_5H_4O_2$

*l.* Polyethylene, monomer $CH_2 = CH_2$

*m.* Polymide film (Kapton), $(C_{22}H_{10}N_2O_5)_n$

*n.* Polymethylmethacralate, monomer $CH_2 = C(CH_3)CO_2CH_3$

*o.* Polystyrene, monomer $C_6H_5CH{=}CH_2$

*p.* Teflon, monomer $CF_2 = CF_2$

*q.* Polyvinyltolulene, monomer 2-$CH_3C_6H_4CH{=}CH_2$

*r.* Bismuth germanate (BGO), $(Bi_2O_3)_2(GeO_2)_3$

*s.* 97% $SiO_2$ + 3% $H_2O$ by weight; see A. R. Buzykaev *et al.*, Nucl. Instrum. Methods **A433**, 396 (1999). Aerogel in the density range 0.04–0.06 g/cm$^3$ has been used in Čerenkov counters, but aerogel with higher and lower densities has been produced. $\rho$ = density in g/cm$^3$.

*t.* G10-plate, typically 60% $SiO_2$ and 40% epoxy.